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Calibration procedure for force and displacement measurements at the HOPLAB

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1. The HOBLAB Facility

The Large Hopkinson Bar (HOPLAB) facility is used for the dynamic testing of material specimens and structural components [1,2]. It is one of the biggest existing Hopkinson bar apparatuses with a total length of more than 200m and bars with diameters of 72mm, made of high-strength steel. Depending on the size of the specimen, strain-rates that can be achieved are between 50/s and 1000/s. Through pre-tensioning and suddenly releasing a steel cable, rectangular force pulses of up to 2MN, 250μs rise time and 40ms duration can be generated and applied to the specimen tested. The cable pre-tensioning is effected with a hydraulic jack, electronically controlled, and the instantaneous release of the opposite cable-end is achieved through breaking of a fragile bolt, which resists all the pretension. The fracture of the bolt is induced by the detonation of a small amount of explosive inserted in it. This high-strength cable is 100m long and has an equivalent diameter of 72mm. The tensile pulse generated is transmitted to the actual incident (input) bar, to the specimen and to the transmitter (output) bar, of about 90m long. The input and output bars are made of bar segments of 5.5 m long rigidly connected with properly designed sleeve joints. At the distal end of the output bar a hydraulic damper allows the dissipation of the remaining energy emanating from the cable and transferred through the specimen to the output bar.

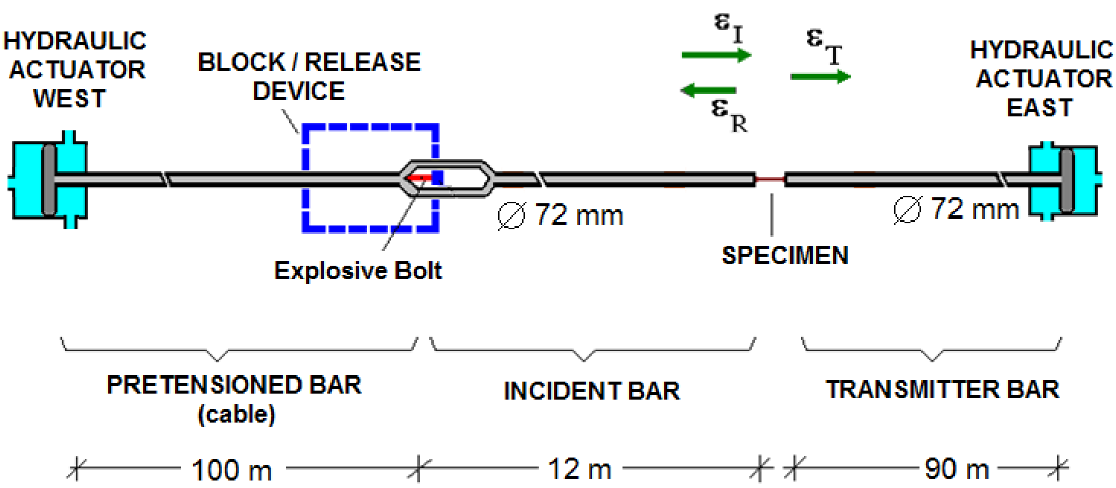


Fig. 1. Sketch and principle of functioning of the HOPLAB facility.

Clearly, in its "natural" configuration the HOPLAB can deliver dynamic tensile pulses in a straight-forward manner, Figure 1. By changing the central part of the equipment it is possible to exploit the tensile wave generated, and to perform different kinds of tests, as for example compression tests.

As explained above, the input pulse is generated by pre-tensioning the input cable with a hydraulic actuator, which is electronically controlled. The management of the liberated elastic energy is a crucial issue, as its value can be in excess of 1MJ. Part of it is consumed at the specimen through deformation and fracture; another part may be dissipated at sacrificial aluminium tubes, properly installed; and a considerable fraction of it may still end up at the actuators. Thus the equipment needs energy damping mechanisms at the end of the input and output bars to absorb part of the energy initially stored in the cable, and also to stop the movement of the bars. This function has been assigned to two hydraulic jacks, one at each extremity of the apparatus, that can operate either as actuators or as dampers. As is understood, this energy management problem is not as acute for the pre-tensioned cable because it is self-relaxing after its release.

The two cylinders have been developed entirely at the ELSA lab of the JRC and their main features include: piston of 400mm diameter, 1m stroke, tubular shaft (external diameter 160mm, internal diameter 80mm), maximum static working pressure 320bars. All the mechanical components of the cylinder have been made of high-strength steel and the actuator is digitally controlled with a proportional servo-valve that connects its two chambers to the input and output pressure lines. Five additional bypasses allow an increased oil flux between the two chambers when the cylinder functions as a damper.

a)


b)


Fig. 2. a) West cylinder and hydraulic pumping station, and b) East cylinder and hydraulic pumping station.

The two actuators/dampers, Figures 1 and 2, are practically identical and differ only in a few functional features. The "West" cylinder exclusively works (without any bypass being activated) as actuator for stretching the input cable. The connection between the input cable and the shaft is rigid. Six gas accumulators (Figure 2a) allow the compensation of the supply pressure when the cable is abruptly unloaded and the pressure in the two chambers needs to rebalance. The "East" cylinder works as actuator only during the test preparation phase, when there is need to move the output bar in order to properly position the specimen. When a dynamic test is going to take place, the cylinder is pressurised and all its bypasses are opened in order to allow it to function as a damper and absorb the energy transmitted there by the output bar. To reduce the pressure peaks, six gas accumulators have been installed on each chamber (Figure 2b). The connection between the output bar and the jack is elastic in the sense that a series of Belleville springs have been mounted between the output bar and the cylinder shaft. The two independent hydraulic power units (one for each actuator) have been manufactured by Moog.

The control of the two jacks is performed by a digital electronic controller developed in ELSA. This allows for the pressurisation and displacements in the actuators to be applied remotely from the control room. Further, both east and west actuators have been instrumented with static (WIKA) and dynamic (Kistler) pressure transducers, and with static (MTS temposonics) and dynamic (SpaceAge Control wire potentiometers) displacement transducers.

Given that the duration of the tests at the HOPLAB is of the order of a few milliseconds, the facility requires a high sampling-rate transient recording system, capable of acquiring electrical signals in three different areas: west end, east end and naturally the specimen zone. This requirement has been fulfilled by employing three respective transient recorders Nicolet MultiPro with a maximum sampling-rate of 1MHz, synchronized with the electrical signal that triggers the explosion of the fragile bolt.

In addition, in order to effectively study the dynamic behaviour of the different moving parts of the equipment (especially during its development phase) and of the tested specimens, a high-speed camera, synchronized with the transient recorders, has been intensively used.

2. The HOPLAB calibration procedure

The analysis of tests according to the Hopkinson bar theory requires the knowledge of three parameters [1,2], as schematically shown in Figure 1: the incident strain pulse $\varepsilon_I(t)$ towards the specimen, the reflected strain pulse $\varepsilon_R(t)$ from the specimen (both in the input bar), and the transmitted strain pulse $\varepsilon_T(t)$ (in the output bar).

In the specimen zone the strain histories are recorded at several fixed positions along the bar with strain-gage sensors, in which a full-bridge setup has been adopted in order to compensate for bending and thermal phenomena. The captured signals are conditioned with a high-speed strain-gage conditioner, a Vishay 2400 with cut-off frequency of 100 kHz.

To check the correct alignment of the equipment and to calibrate the strain-gages mounted on the bars an accurate calibration procedure is essential.


Fig. 3. The HBM-STZ 1MN load cell and the HBM MGCplus system.

The complete calibration procedure of the HOPLAB facility in general takes place before any test campaign and occasionally for confirmation purposes at the end of the tests, if some problems/changes have occurred during their execution. According to ISO9001 policy, the equipment calibration is carried out using certified reference devices that are annually checked and calibrated by a metrology laboratory.

The fundamental physical quantity that must be calibrated and accurately recorded in a Hopkinson Bar testing is the force (or equivalently the strain) applied to / transmitted through the bar. In order to achieve this target a precision load cell, an HBM model STZ of 1 MN maximum force, and a high precision strain-gage amplifier, an HBM MGCplus, are used (Figure 3). In practice the load cell is placed in series with the equipment bars and loaded by the two actuators/dampers from the equipment ends. As shown in Figure 4, no explosive bolt is used in this stage. The east actuator is held fixed in the initial position, while the west actuator loads slowly the cable and the whole bar system.

In the tensile test setup the load cell is directly connected to the bars with a screw connection, Figure 4, whereas in compression test setup two spherical joints are adopted to avoid bending loads on the load cell, Figure 5.

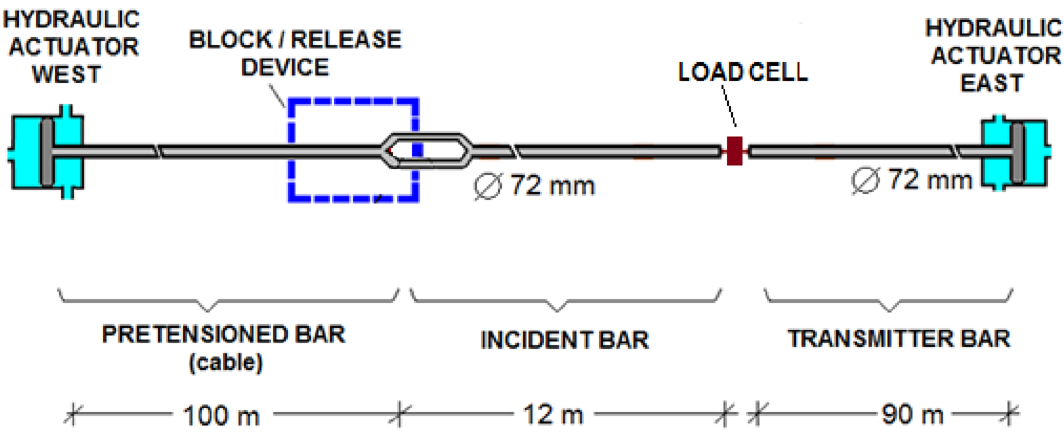


Fig. 4. Static calibration of strain-transducers in a tensile test setup.

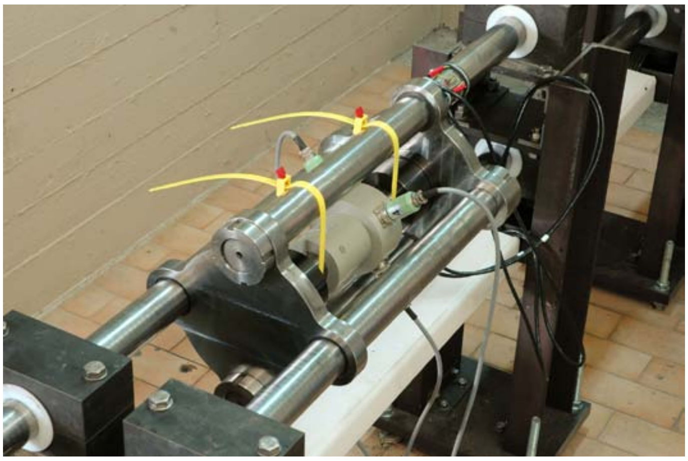


Fig. 5. Detail of static calibration of strain-transducers in a compression test setup (twin input, twin output bars are used with plates attached to their ends, respectively).

Comparing the signals obtained with the calibration device (HBM STZ plus HBM MGCplus) and with the standard acquisition system (strain-gage plus strain-gage amplifier Vishay 2400 plus transient recorder Nicolet MultiPro), it is possible to simultaneously calibrate the force acquisitions in all the measurement points of the equipment by adopting suitable proportionality coefficients. These coefficients may differ from their respective predicted values due to several unknown factors of the equipment-sensors-instruments system, such as: the misalignment of strain-gages, the variability of strain-gage k-factors, the calibration error of the transient recorder, etc. In addition, using this procedure, the accuracy and the repeatability of the equipment measurement system can be reliably evaluated and representative statistics of data can be extracted.

In the next paragraph the detailed procedure is being schematically presented and a brief description of data analysis is shown.

Steps of the Force Calibration Procedure

- Zeroing of strain-gage sensors and load cell without any pre-load. In the compression setup this can be simply reached by maintaining a small gap between the spherical joints and the equipment loading plate. In the tensile setup a small slack must be incorporated in the screw connection between the bars and the load cell (at least on one side)

- Start the recording of the strain-gages signals with the standard transient recorder and of the force signal with the reference device, using an appropriate sampling. In general a sampling rate of 100 Hz has been adopted for this static loading and the acquisition lasts approximately 600 s. The two samplings must be synchronized with an external trigger and sync.

- The whole equipment is put in tension by controlling the two actuators at the equipment ends (displacement control). Since no explosive bolt is present, the west actuator loads slowly the system cable/input bar/load cell/output bar up to 1 MN. In general a loading and unloading path is repeated and recorded for three times in order to verify the repeatability of the measurements.

- The two sets of data are compared, linearity is checked and the appropriate proportionality coefficients (one for each strain-sensor) are calculated through a standard regression analysis. This also allows statistics on the accuracy and repeatability of the data acquisition to be estimated.

To better illustrate the steps for the calculation of the proportionality factors an example with specific, actual data is presented.

By applying the above calibration procedure, a set of voltage histories (one for each strain-sensor, Figure 6a) and a force history (from the reference device, Figure 6b) are acquired. The output voltage from each strain-gage is plotted against the reference force history, and a linear relationship is in general expected to be verified. Through a standard regression analysis it is thus possible to evaluate the proportionality coefficient for each strain-gage measurement point on the bar. In Figure 7, for example, this coefficient would be (approximately) equal to 263 kN/V. It must be emphasised that the two data sets have to be acquired in the same time instants and for this reason the two sampling devices must be hardware synchronized (with a trigger and a sync signal). At this point accuracy, repeatability and hysteresis of the measurement system can be effectively evaluated and statistics about these factors can be extracted [3].

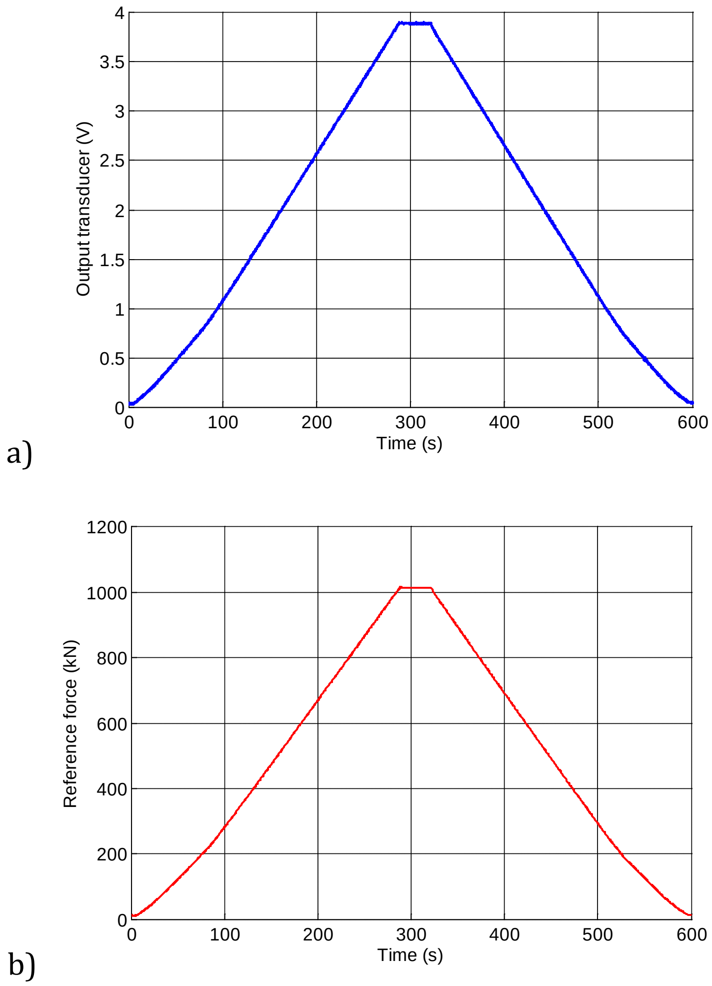


Fig. 6. a) Voltage signal from a strain-gage measurement, and b) force signal simultaneously recorded in the reference calibration device.

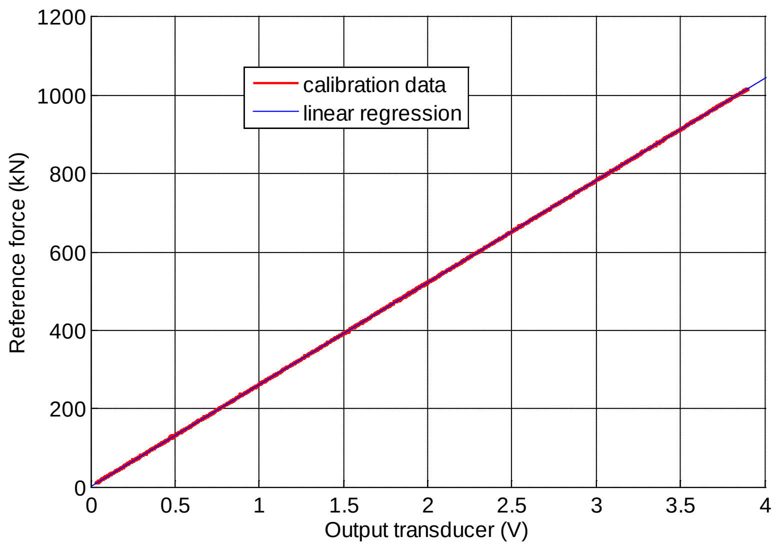


Fig. 7. Output voltage from a transducer vs. reference force.

In addition, it is advisable that the correct mounting of the reference load cell is evaluated by comparing its four force output signals (at 0º, 90º, 180º and 270º positions, Figure 3). As shown in Figure 8, even if the mean value is always representative of the axial force transmitted to the bar, it is always better to keep the differences to less than 10% in order to limit bending loads on the reference load cell.

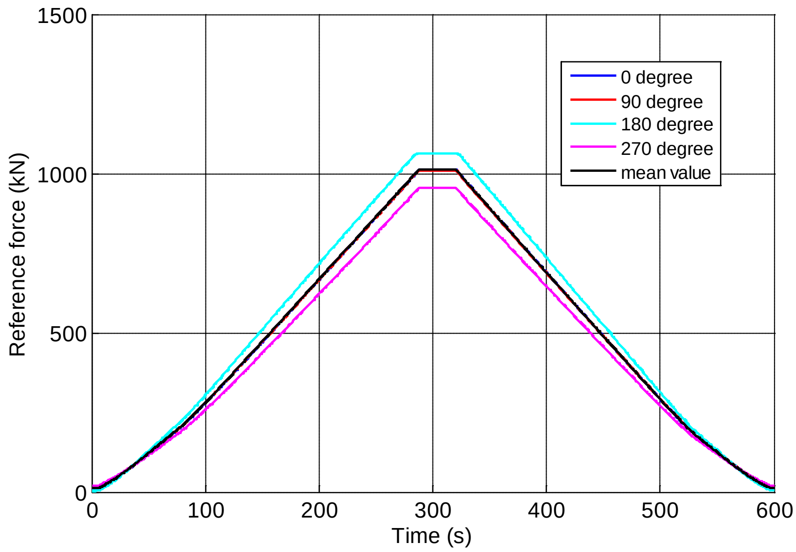


Fig. 8. Force output signals of reference load cell.

Finally, for good practice it is suggested that an additional check be made during this procedure of the HOPLAB force calibration. It consists of comparing the load transmitted to the central portion of the bars (where they are instrumented) with the forces applied at the two ends of the equipment (Figure 4) by the hydraulic actuators.

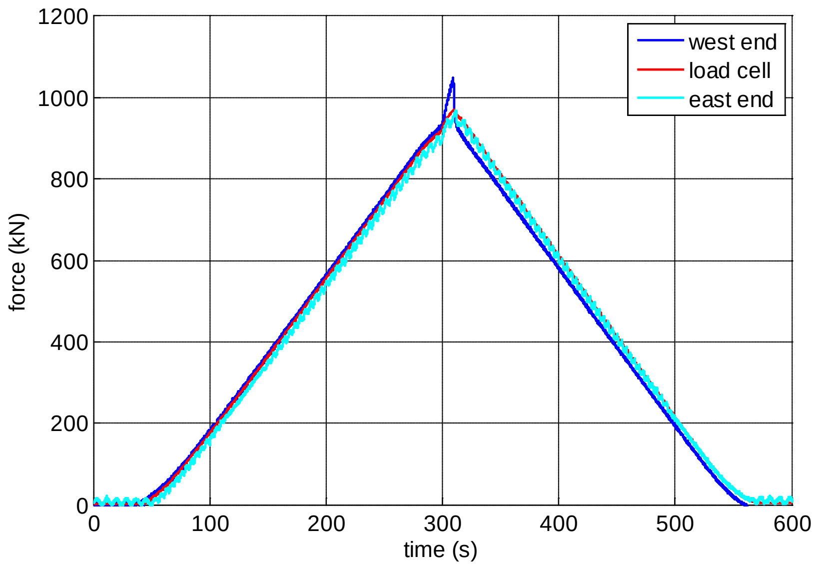


Fig. 9. Comparison of force signals at three different equipment locations.

The forces at the actuators, Figure 9, are calculated by simply multiplying the oil net pressure at the chambers by the effective cross-section of the pistons. It must be noted that these measurements are obtained with pressure sensors not periodically certified and for this reason these data are only indicative of the correct functioning of the equipment. However, they are useful especially for safety, as in this way the friction along the cable and between bar and supports can be checked and accidental malfunctioning can be indentified in advance.

Determination of apparatus parameters

The particular operating principles of a Hopkinson Bar equipment [1,2], and consequently of the HOPLAB facility, require the knowledge of certain parameters of the machine and of the specific test setup. These are obtained through a series of preliminary tests, which must be performed in the order presented below in order to evaluate the parameters of interest correctly.

Positions of measurements on equipment bar (in time domain)

To simplify the elaboration of data acquired in a dynamic test with a Hopkinson Bar and to correctly reconstruct the force-displacement curve applied by the equipment to the specimen it is essential to know the exact time shift (or time delay) between the different measurement points along the equipment bar. This can be effectively done by performing a dynamic void test (a test without the specimen and with the input/output bars rigidly connected) and by accurately measuring the delay in the arrival times of the propagating wave, as recorded at the different measurement locations.

Young modulus of equipment bar material

Knowing the time shift and the geometrical distance between two measurement points on the bar, the bar wave speed c_0 can be readily calculated, which, as recalled, depends on the material Young modulus E and density ρ. Through the well-established relationship $c_0=(E/\rho)^{1/2}$ the Young modulus can thus be determined. The Young modulus, according to the wave propagation theory in elastic media, is fundamental for the calculation of particle velocities and displacements along the bar when the forces are known, these latter being recorded via the strain-gages placed on the bar surface.

3. Example of dynamic tensile tests

The elaboration of data acquired during a Hopkinson Bar dynamic test may present a series of specific problems connected to wave propagation phenomena in elastic bars, such as transmissions and reflections through boundaries, wave dispersion etc. To better illustrate the main issues of an advanced Hopkinson Bar data elaboration, a small example is included below relative to the dynamic tensile testing of a steel specimen, Figure 10. Some details are discussed and a typical elaboration of the raw experimental data is demonstrated.

Fig. 10. Steel dumb-bell shaped specimen of 30 mm diameter.

Figure 11 shows a standard experimental configuration of the HOPLAB and Figure 12a shows the data acquired during the test in four different positions: the first two signals (blue and red) on the input bar and the other two signals (cyan and magenta) on the output bar. As readily observed from the signals of the output bar, the test lasts approximately 25 ms (cyan curve rises at ~2.5 ms and falls abruptly to zero at 27.5 ms following the specimen rupture).

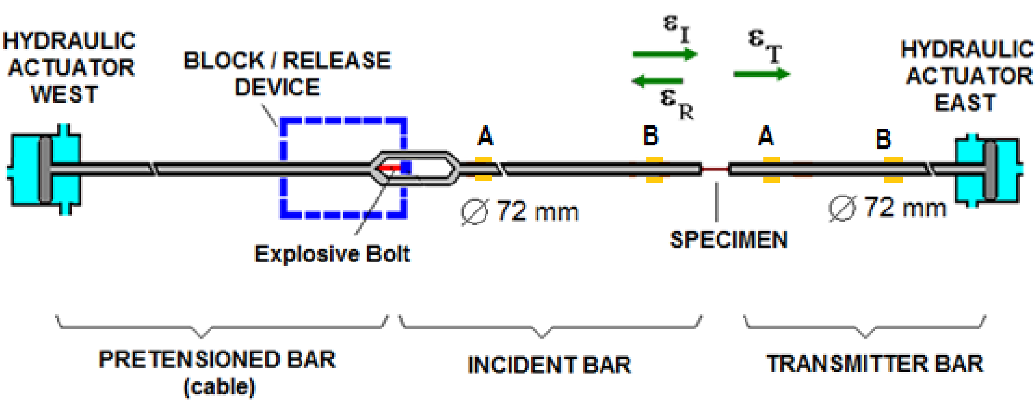
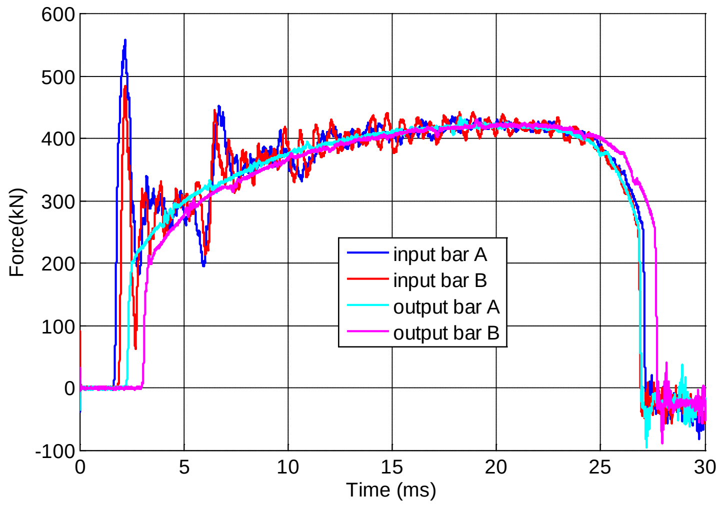


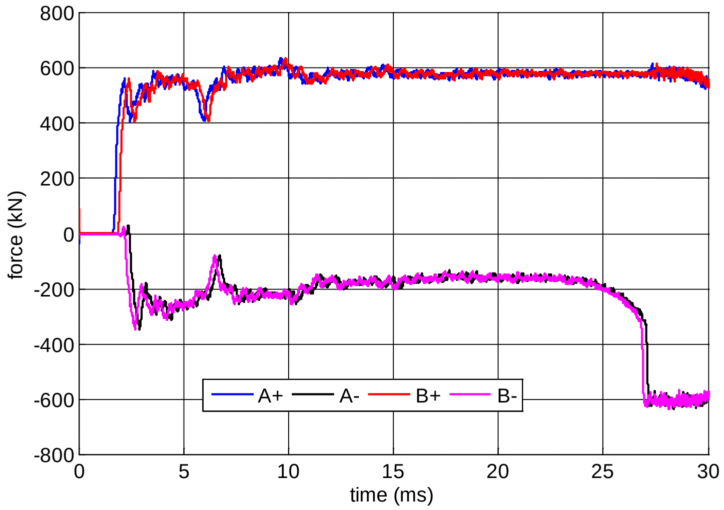
Fig. 11. Typical dynamic tensile test and positions of four strain-gage stations along the bars.

At this point it is necessary to separate ascending and descending waves (that travel in opposite directions through the bars), normally by using an iterative algorithm [4].

This technique allows the identification of the incident, the reflected and the transmitted waves, which are indispensable to apply the conventional Hopkinson Bar relations to evaluate the displacement and the force applied to the specimen. Following this elaboration, Figure 12b presents these separated ascending and descending waves for the input bar. The symbols "A" and "B" stand for the measurement locations on the input bar and the symbols "+" and "-" signify ascending and descending waves, respectively.



a)

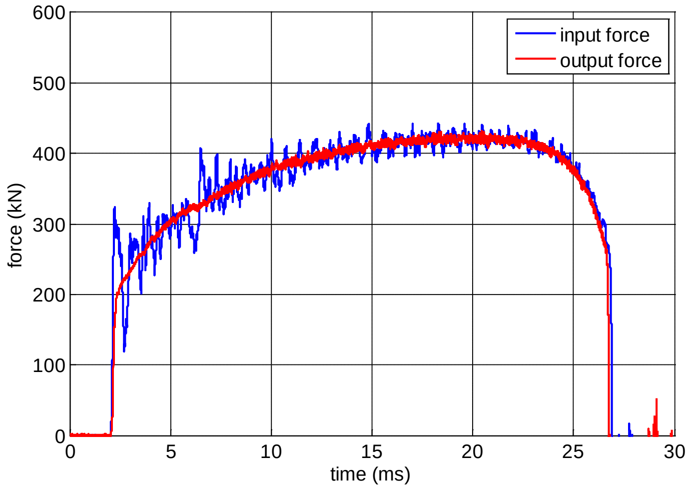


b)

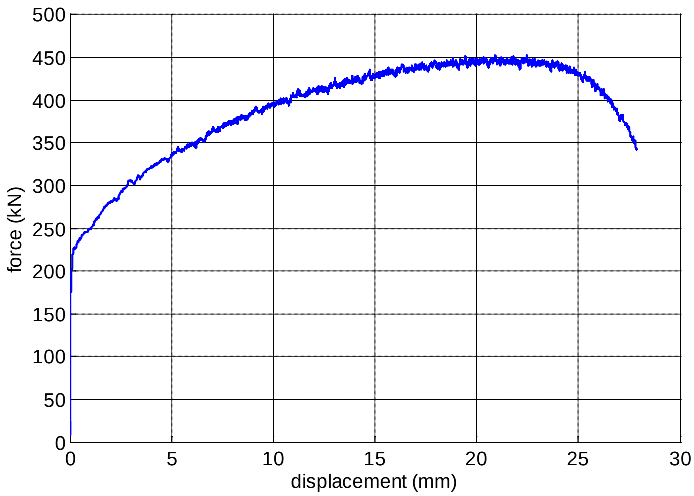
Fig. 12. a) Recorded force (strain) signals along the bars, and b) separated waves in the input bar.

To increase the accuracy of the separation procedure it is suitable to compensate for wave pulse distortions due to dispersion phenomena. This correction is especially needed in the case of a large bar cross-section and/or relatively small wave length, and is based on the exact (Pocchammer-Chree) wave propagation theory in bars [5]. In addition, since the HOPLAB bars are not monolithic but are made of 5.5m-long segments, it is advantageous to apply the procedure to signals acquired in the same bar section because the slack in the connections between bar segments can appreciably affect the accuracy of this method.

The force equilibrium at the specimen ends must next be checked by synchronising the incident, the reflected and the transmitted waves by means of a time shifting. As can be verified in Figure 13a, despite the large length of the specimen used (compared with standard Hopkinson Bar specimens) the equilibrium is reached and maintained during all instants of the test. Finally Figure 13b shows the force-displacement curve applied to the specimen by the equipment. It is observed that no reflections or ringing phenomena affect this curve even though the test lasts for approximately 25 ms. Division of the displacement by the specimen gage-length and of the force by the cross-sectional area, respectively, would produce the relevant dynamic stress-strain (σ-ε) diagram of this material.



a)



b)

Fig. 13. a) Equilibrium check at specimen ends and b) force-displacement curve applied to the specimen.

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Abstract
The report explains the calibration procedure of the HOPLAB facility. A short description of the facility is first included concerning the mechanical structure and its equipment in terms of sensors, transducers and relevant electronic instruments. A detailed explanation of the calibration procedure is next presented, which is principally centred at calibrating the force measurements along the input and output bars with a certified load cell. The main issues and problems connected to this particular testing rig are discussed. Finally an example of a typical elaboration, starting from raw experimental data to obtain the force-displacement curve of a specimen in tension, is provided.

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